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Bioactive glass composition

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BIOACTIVE GLASS COMPOSITION

(98)

FIELD OF THE INVENTION

5 This invention relates to a bioactive glass composition comprising SiO_2 , Na_2O , CaO , K_2O , MgO , P_2O_5 and B_2O_3 . The invention further relates to the use of said composition and devices manufactured from it. The invention still relates to a method for manufacturing a bioactive glass composition according to the present invention.

BACKGROUND OF THE INVENTION

10 The publications and other materials used herein to illuminate the background of the invention, and in particular, the cases to provide additional details respecting the practice, are incorporated by reference.

15 In this application, by bioactive glass is meant a material that has been designed to induce specific biological activity in body tissue. The term biodegradable in this context means that it is degradable upon prolonged implantation when inserted into the mammal body. By biomaterial a non-viable material used in a medical device is meant, a material that is intended to interact with biological systems.

20 Glasses have been studied extensively for applications in medical and dental surgery and implants. A medical device can be implanted into any human or animal tissue. This allows local application so that targeting of the biologically active agent release site is possible. Since only a non-crystallized glass composition shows the best bioactivity and since bioactive glass compositions are in the area near the phase separation, it is very difficult to
25 make glass compositions that do not crystallize during repeated heat treatment, i.e. that remain bioactive.

30 Bioactive glasses develop reactive layers on their surfaces resulting in bonding between the device and the host tissue. Unlike most other bioactive materials, the rate of chemical reactions of bioactive glasses can be easily controlled by changing the chemical composition of the glass. Therefore, bioactive glasses are interesting in particular in clinical applications and have indeed been used for example to replace damaged parts of facial injuries,

replacement of the small bones (ossicles) in the middle ear and in surgery to fill defects in bone.

Unfortunately, the traditionally known bioactive glass compositions do not support repeated heat-treatments, since reheating results in a decrease of the bioactivity. This causes great problems in the manufacturing of devices from these compositions, since they can only be shaped by molding them into the final shape already in the production step of the glass or by crushing the previously formed glass particles. The molding process only allows the production of rigid non-porous devices.

An improved bioactive glass composition with respect to the heat-treating properties has been presented by Brink et al. in WO 96/21628. This document discloses a bioactive glass of the following composition:

SiO₂ in an amount of 53 - 60 wt-%,
Na₂O in an amount of 0 - 34 wt-%,
K₂O in an amount of 1 - 20 wt-%,
MgO in an amount of 0 - 5 wt-%,
CaO in an amount of 5 - 25 wt-%,
B₂O₃ in an amount of 0 - 4 wt-%,
P₂O₅ in an amount of 0,5 - 6 wt-%,

provided that

Na₂O + K₂O = 16 - 35 wt-%
K₂O + MgO = 5 - 20 wt-%, and
MgO + CaO = 10 - 25 wt-%.

The heat-treating properties of these glasses are however not optimal for repeated heating when devices for technically demanding applications of bioactive glass are manufactured (for example fibers, sintered fiber fabrics etc.).

The publication by Itälä et al., published in Journal of Biomedical Materials Research (2001) 56 (2), pages 282-288, discloses a bioactive glass having the following composition:

SiO₂ in an amount of 53 wt-% of the starting oxides,
Na₂O in an amount of 6 wt-% of the starting oxides,

- CaO in an amount of 22 wt-% of the starting oxides,
K₂O in an amount of 11 wt-% of the starting oxides,
MgO in an amount of 5wt-% of the starting oxides,
P₂O₅ in an amount of 2 wt-% of the starting oxides, and
5 B₂O₃ in an amount of 1 wt-% of the starting oxides.

This document does however not discuss the properties of the glass composition when heated repeatedly.

OBJECTS AND SUMMARY OF THE INVENTION

- 10 The object of this invention is to provide a bioactive glass composition that can be repeatedly heat-treated without the crystallizing of the glass and losing its bioactive properties. A further object of this invention is to provide a bioactive glass composition that is suitable for manufacturing devices for technically demanding applications of bioactive glass.

DETAILED DESCRIPTION OF THE INVENTION

- 15 The invention is disclosed in the appended claims.

The bioactive glass composition according to the invention is characterized in that the amount of

- 20 SiO₂ is 51-56 wt-% of the starting oxides,
Na₂O is 7-9 wt-% of the starting oxides,
CaO is 21-23 wt-% of the starting oxides,
K₂O is 10-12 wt-% of the starting oxides,
MgO is 1-4 wt-% of the starting oxides,
P₂O₅ is 0,5-1,5 wt-% of the starting oxides, and
B₂O₃ is 0-1 wt-% of the starting oxides,

- 25 provided that the total amount of Na₂O and K₂O is 17-20 wt-% of the starting oxides.

Thus, the invention concerns a bioactive glass composition that can be heat-treated even repeatedly.

- 30 The Applicants have indeed found that a bioactive glass having the above-mentioned composition has unexpected and surprisingly good heat-treating properties. The present invention is thus a selection invention of the above-

mentioned invention disclosed in WO 96/21628. Indeed, the selected sub-range is narrow compared to the range disclosed in WO 96/21628, it is far removed from the end-points of said range of WO 96/21628 and it is a purposive selection since having an unexpected technical effect.

- 5 The amount of different oxides is given as weight percent of the starting oxides because some elements, such as sodium, evaporate during the heating. The amounts of the final oxides are however close to those of the starting oxides and in any case, the difference between the starting amounts and the final amounts is less than 5 percentage units, preferably less than 3 percentage
10 units.

- It is obvious to a person skilled in the art that the amounts of the oxides can be freely chosen within the above-mentioned limits. Indeed, the amount of SiO_2 can be for example 51,5, 52, 53,5, 55 or 56 wt-% of the starting oxides, the amount of Na_2O can be for example 7, 7,3, 7,7, 8, 8,5 or 9 wt-% of the
15 starting oxides, the amount of CaO can be for example 21, 21,4, 21,7, 22, 22,6 or 23 wt-% of the starting oxides, the amount of K_2O can be for example 10, 10,5, 10,6, 11, 11,3, 11,7 or 12 wt-% of the starting oxides, the amount of MgO can be for example 1, 1,3, 1,9, 2,4, 2,7, 3,5 or 4 wt-% of the starting oxides, the amount of P_2O_5 can be for example 0,5, 0,7, 1, 1,2 or 1,5 wt-% of
20 the starting oxides, and the amount of B_2O_3 can be for example 0, 0,4, 0,6, 0,9 or 1 wt-% of the starting oxides.

According to an embodiment of the invention, the amount of SiO_2 is 54-56 wt-% of the starting oxides

- 25 According to another embodiment of the invention, the inventive glass composition further comprises Al_2O_3 up to 1 wt-% of the starting oxides provided that the total amount of B_2O_3 and Al_2O_3 is 0,5-2,5 wt-% of the starting oxides.

- 30 According to yet another embodiment of the invention, the decrease in the amount of Na_2O and/or K_2O is compensated by the increase of the amount of Al_2O_3 and/or B_2O_3 .

It is believed that the role of bioactive glass in bone formation is two-fold: to supply Ca^{2+} ions and to form a silica gel layer on the surface of the glass. This gel acts as a diffusion barrier, thus slowing down the leaching of ions from the glass and accordingly slowing down the formation of the new

reaction layers and new body tissue. The silica gel is also acidic and may therefore irritate the tissues.

5 A further advantage of the bioactive glass composition according to the invention is that the primary reaction of a device manufactured from the inventive glass composition with the body tissue is "gentle", i.e. not so aggressive as with some traditional bioactive glasses. Indeed, firstly calcium phosphate is formed in the relatively thin layer into the silica gel on the surface of the glass, typically in about 6 hours and secondly, a calcium phosphate layer is formed on the layer of silica gel, typically in about 48-72
10 hours. During the formation of the primary calcium phosphate, the layer of silica gel on the surface of the inventive glass composition is essentially thinner than the corresponding layer on a traditional bioactive glass, for example as the one identified above.

15 In other words, the bioactive glass composition according to the invention reacts in to an appropriate extent and does not dissolve too much, which is obviously an advantage in situations *in vivo*. On the other hand, a device manufactured from the inventive composition remains bioactive for a long period of time.

20 This advantage of the composition allows its use in target organs that are very sensible, such as cornea. The inventive glass composition reacts with the tissue in a gentle way, thereby reducing the chemical irritation due to the formation of the silica gel layer, for example. The properties of the inventive glass composition also allow it to be used in a powder having smaller particles than the traditional compositions, thus further decreasing the
25 irritability of the composition.

Other suitable target organs are for example organs having a poor blood circulation such as sinuses or the bones of elderly patients. The present bioactive glass composition may also advantageously be used to recreate tissues that have disappeared due to an infection.

30 The bioactive glass composition according to the invention thus has an increased ability to react in a controlled and desired manner. Furthermore, it can be manufactured into any desired device according to conventional manufacturing methods and thus it may be used in applications requiring especially accurate devices and conditions.

Indeed, the bioactive glass having a composition according to the invention may be processed with any conventional methods. It may for example be firstly made into a solid glass that is further crushed. The composition according to the invention has the further advantage that it is possible to make
5 granules thereof having a particularly well-controlled particle size distribution. These granules can be further heated to obtain spheres that may yet further be sintered to obtain a porous device of any desired shape. It is yet further possible to use the spheres or other particles of the bioactive glass for different casting processes such as pressure casting or for the casting of a thin
10 sheet of glass with a process similar to the production of window glass.

A particularly preferred method for the treatment of the present bioactive glass composition is heating with laser since it allows localized yet high temperatures to be used in the melting of the glass.

The devices according to the invention may be in various forms, e.g., in the
15 form of a particle, a disc, a film, a membrane, a tube, a hollow particle, a coating, a sphere, a semi sphere or a monolith, and they may have various applications.

Also fibres, granulates, woven and nonwoven mats, tissue-guiding devices as well as films may be manufactured. By tissue-guiding device a device is
20 meant that has such properties that once in place in the patient's body it guides the formation of different types of tissues on different portions of the device. It may also be a device of a desired shape having various channels through its body in order to guide the formation of a vein in these locations.

Especially interesting forms of the present bioactive glass composition are
25 fibre rovings, a perforated plate or sheet and a woven tissue having a precise profile. A perforated plate or sheet may be manufacture by casting or weaving and the diameter of the perforations is typically in the range of 10-500 μm . By a woven tissue having a precise profile it is meant a tissue wherein the position of the fibres is determined with a precision of micrometers.

30 The bioactive glass composition according to the invention may also be used for the coating of a device. The coating may be performed either by casting or dipping or a device may be coated with crushed particles of bioactive glass that is then sintered. The bioactive glass composition according to the invention may especially advantageously be used in the coating of ceramic

materials since the heat expansion coefficients of the glass and ceramics do not significantly deviate from each other. It is also possible to use the present bioactive glass composition for the coating of metal such as titanium. A further advantage of the present composition is that it undergoes the treatment
5 without crystallizing.

Tooth-implants, hip-implants, knee-implants, mini plates, external fixation pins, stents (e.g. for use in repair of blood vessels) or any other implants can be coated with the inventive glass composition.

10 The glass according to the present invention is advantageously prepared in atmospheric pressure and at temperatures of about 1360 °C. The heating time for making the glass melt is typically three hours. No protection gas is needed. When preparing the glass composition according to the present invention, the constituents are first melted together and then cooled down. The resulting solid material is then crushed and remelted in order to obtain a
15 homogeneous material.

A porous device may also be manufactured by injecting pressurized gas into the glass melt, for example during the casting of the glass. If pressurized air is used, the conventional glass crystallizes due to the low temperature of the air. This problem does however not occur with the inventive glass composition
20 and therefore both open- and closed-celled structures may be formed. The pores may further be filled by some active agents. Porosity of the bioactive glass does not only noticeably increase the total reacting surface of the glass but also allows a three-dimensional formation of the healing bone tissue.

25 The inventive glass composition can further be used in the manufacturing of different composites and devices consisting of at least two materials, such as a combination of bioactive glass and a metal or a ceramic material.

The bioactive glass composite may comprise different materials such as polymers, metals or ceramics. In applications in which the device needs to dissolve, it is preferable to use for example biopolymers. Either polymers
30 based on renewable raw materials, e.g. cellulose, or synthetic polymers that are biodegradables, e.g. polylactides are meant by "biopolymer".

A composite may be formed using the inventive bioactive glass composition as a matrix and a ceramic material as reinforcing component. The inventive composition is especially suitable for matrix due to its crystallization

properties. The inventive composition also glues the reinforcing particles or fibers strongly together. An implant manufactured from such a composite quickly becomes porous once in contact with the body tissue, a property that is desired in some applications, such as devices for tissue engineering.

- 5 The additives or reinforcements used in the composites may be in various forms such as fibres, woven or nonwoven mats, particles or hollow particles. They may also be porous or dense materials, and it is obvious that they are preferably biocompatible.

10 An especially advantageous use of the present glass composition is in the form of fibres. Indeed, the present composition may be drawn to a fibre at higher temperatures than the known bioactive glass compositions. Typically, the manufacturing temperature may be even 100 °C higher than for the conventional bioactive glass compositions. Higher manufacturing temperatures lead to fibres having a smaller diameter since the viscosity of the glass melt decreases with increasing temperature. Also, the manufacturing temperature is critical for the resulting fibre product since it is close to the softening temperature of the glass, thus close to the crystallization temperature. A fibre manufactured from the present composition has then been heat-treated three times and it still has the described properties.

- 20 A further advantage of the present glass composition is its better stability during storage. Indeed, the glass composition may react with the humidity of air during storage. Therefore, a glass composition according to the present invention which has a homogeneous structure will react uniformly and the product after storage still has predictable properties.

- 25 It was stated above that the amounts of the final oxides is close to those of the starting oxides. As an example, when the theoretical composition of the final glass was:

30 SiO₂ 53 wt-%,
P₂O₅ 2 wt-%,
CaO 22 wt-%,
Na₂O 6 wt-%,
K₂O 11 wt-%,
MgO 5 wt-% and
B₂O₃ 1 wt-%,

then the amounts of the oxides in the final bioactive glass composition were, as analysed by EDX (Energy dispersive X-ray analysis):

5 SiO₂ 55,17 wt-%,
 P₂O₅ 2.11 wt-%,
 CaO 21.53 wt-%,
 Na₂O 5.64 wt-%,
 K₂O 9.46 wt-%,
 MgO 5.09 wt-% and
 B₂O₃ 1.00 wt-%.

- 10 The present invention further relates to a method for manufacturing a repeatedly heat-treatable bioactive glass composition according to the present invention, the method being characterized in that it comprises the steps of
- a) heating a mixture of starting materials to a temperature of 1350-1450 °C for a period of essentially three hours,
 - 15 b) allowing the obtained melt to cool down to ambient temperature for at least twelve hours,
 - c) crushing the obtained glass composition into pieces,
 - d) reheating the crushed glass composition to a temperature of 1350-1450 °C for a period of essentially three hours, and
 - 20 e) molding the obtained bioactive glass composition into desired shape and allowing it to cool down to ambient temperature.

25 The method according to the present invention thus comprises two steps of melting or heating the composition in order to obtain a homogeneous mixture. The final bioactive glass composition can be cast or mold to any desired shape such as directly into the form of a sheet or a rod that can be further made into fibre or into a solid block that is used in the conventional way, i.e. crushed into pieces and reheated to be mold.

30 In this specification, except where the context requires otherwise, the words "comprise", "comprises" and "comprising" means "include", "includes" and "including", respectively. That is, when the invention is described or defined as comprising specified features, various embodiments of the same invention may also include additional features.

The invention is described below in greater detail by the following, non-limiting drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates an example of a device for tissue engineering comprising the inventive glass composition.

5 Figure 2 illustrates a cross-section of a bioactive fabric comprising the inventive glass composition.

Figure 3a illustrates the reaction of a fibre made from conventional bioactive glass when in contact with a body fluid.

Figure 3b illustrates the reaction of a fibre made from the inventive bioactive glass when in contact with a body fluid.

10 Figure 4a shows a scanning electron microscope picture of a bioactive glass fiber according to the present invention at a magnification of x100.

Figure 4b shows a scanning electron microscope picture of a bioactive glass fiber according to the present invention at a magnification of x500.

15 Figure 5a shows a scanning electron microscope picture of a bioactive glass fiber according to the present invention at a magnification of x100 and after immersion in Tris for 7 days.

Figure 5b shows a scanning electron microscope picture of a bioactive glass fiber according to the present invention at a magnification of x500 and after immersion in Tris for 7 days.

20 DETAILED DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates an example of a device for tissue engineering comprising the inventive glass composition. The device 1 comprises glass particles or short fibers 2 manufactured from the glass composition according to the present inventive bioactive glass composition and a matrix formed of a biopolymer 3. The degradation rate of the biopolymer is preferably superior to the dissolution rate of the bioactive glass. Therefore, the biopolymer 3 degrades and allows the formation of body tissues such as blood vessels whereas the bioactive glass remains essentially of a constant shape and size. This kind of tissue engineering device allows the formation of new tissues at the desired rate and shape while maintaining unchanged the cavity wherein

the device is implanted. The biopolymer may also comprise a biological molecule such as growth hormone.

Figure 2 illustrates a cross-section of a bioactive fabric comprising the inventive glass composition. The fabric consists, in this embodiment, of three layers of fibers and can be either woven or nonwoven. The respective layers 4, 5 and 6 are manufactured from at least two different compositions of bioactive glass, each composition having a different bioactivity. The layer 4 may be manufactured from the inventive glass composition that maintains its bioactivity unchanged through the manufacturing of the fabric. The layers 5 and 6 may then be manufactured from glass compositions which bioactivities are either altered by the manufacturing process of the fabric or that are not bioactive at all.

Figure 3a illustrates the reaction of a fiber 7 made from conventional bioactive glass when in contact with a body fluid. The Figure shows that the fiber has a heterogeneous structure consisting of a partially crystallized part 8 and an amorphous part 9. The amorphous part 9 has dissolved at a greater rate than the crystallized part 8 thus leading to an uneven cross-section of the reaction layers on the fiber.

Figure 3b illustrates the reaction of a fiber 10 made from the inventive bioactive glass when in contact with a body fluid. The homogeneous structure of the inventive material is clearly shown by the essentially even cross-section of the reaction layers on the fiber after reaction with a body fluid.

Figures 4a to 5b are discussed below.

EXAMPLE

A composition consisting of:

165,00 g of SiO_2 ,
 7,27 g of $\text{CaH}(\text{PO}_4)\text{x}2\text{H}_2\text{O}$,
 108,21 g of CaCO_3 ,
 41,04 g of Na_2CO_3 ,
 48,42 g of K_2CO_3 ,
 9,00 g of MgO , and
 5,33 g of H_3BO_3

was heated to a temperature of 1360 °C and maintained in this temperature for a period of three hours. The melted composition wherein the carbonates had reacted forming oxides was allowed to cool down to ambient temperature overnight and the solid glass was crushed into pieces.

- 5 The crushed glass material was reheated to a temperature of 1360 °C and maintained in this temperature for a period of three hours. The resulting softened glass composition was cast into a mold and allowed to cool down to ambient temperature overnight. 300 g of bioactive glass according to the present invention was obtained. The composition of the glass was the
10 following:

SiO₂ 55 wt-%,
P₂O₅ 1 wt-%,
CaO 21 wt-%,
Na₂O 8 wt-%,
15 K₂O 11 wt-%,
MgO 3 wt-% and
B₂O₃ 1 wt-%.

- The bioactive glass composition obtained was used for drawing of a fiber by standard method and manufacturing a bioactive glass fabric by a nonwoven
20 method. In said nonwoven method, the fibers were bonded to each other by using a thin layer of an aqueous solution of starch. Said solution also acted as a sizing agent thus increasing the strength of the fabric.

- The resulting product was tested by immersing the fabric in Tris for 3, 5 and 7 days, respectively. Precipitation of calcium phosphate occurred at 5-7 days.
25 Optical and X-ray analysis showed no crystals on or in the fibers.

- Figures 4a to 5b illustrate the results of the testing. Figure 4a shows a scanning electron microscope (SEM) picture of a bioactive glass fiber according to the present invention at a magnification of x100 and Figure 4b shows the same sample at a magnification of x500, i.e. the clean surface for
30 comparison.

Figure 5a shows a scanning electron microscope picture of a bioactive glass fiber according to the present invention at a magnification of x100 and after immersion in Tris for 7 days and Figure 5b shows the same sample at a magnification of x500. In Figures 5a and 5b one can see a clear, irregular

reaction surface that, in a mineral analysis, was identified as containing calcium phosphate (CaP) and silicon (Si). The bioactive glass according to the present invention thus reacts in a uniform manner, thus showing that the constitution of the glass is homogeneous.

CLAIMS

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1. A bioactive glass composition comprising SiO_2 , Na_2O , CaO , K_2O , MgO , P_2O_5 and B_2O_3 , **characterized** in that the amount of

- 5 SiO_2 is 51-56 wt-% of the starting oxides,
- Na_2O is 7-9 wt-% of the starting oxides,
- CaO is 21-23 wt-% of the starting oxides,
- K_2O is 10-12 wt-% of the starting oxides,
- MgO is 1-4 wt-% of the starting oxides,
- P_2O_5 is 0,5-1,5 wt-% of the starting oxides, and
- 10 B_2O_3 is 0-1 wt-% of the starting oxides,

provided that the total amount of Na_2O and K_2O is 17-20 wt-% of the starting oxides.

2. A bioactive glass composition according to claim 1, **characterized** in that the amount of SiO_2 is 54-56 wt-% of the starting oxides.

15 3. A bioactive glass composition according to claim 1 or 2, **characterized** in that it further comprises Al_2O_3 up to 1 wt-% of the starting oxides provided that the total amount of B_2O_3 and Al_2O_3 is 0,5-2,5 wt-% of the starting oxides.

20 4. A bioactive glass composition according to any of the preceding claims, **characterized** in that the decrease of the amount of Na_2O and/or K_2O is compensated by the increase of the amount of Al_2O_3 and/or B_2O_3 .

5. Use of a bioactive glass composition according to any of the preceding claims in the coating of a device.

25 6. An implantable device, **characterized** in that it has been prepared from a bioactive glass composition according to any of the claims 1-4.

7. A fiber, **characterized** in that it has been prepared from a bioactive glass composition according to any of the claims 1-4

8. A sheet, **characterized** in that it has been prepared from a bioactive glass composition according to any of the claims 1-4.

9. A porous device, **characterized** in that it has been prepared from a bioactive glass composition according to any of the claims 1-4 by injecting
~~pressurized gas into the molten glass composition.~~

10. A tissue engineering device, **characterized** in that it has been prepared
5 from a bioactive glass composition according to any of the claims 1-4.

11. A method for manufacturing a repeatedly heat-treatable bioactive glass composition according to any of the claims 1-4, **characterized** in that it comprises the steps of

- 10 a) heating a mixture of starting materials to a temperature of 1350-1450 °C for a period of essentially three hours,
- b) allowing the obtained melt to cool down to ambient temperature for at least twelve hours,
- c) crushing the obtained solid glass into pieces,
- 15 d) reheating the crushed glass material to a temperature of 1350-1450 °C for a period of essentially three hours, and
- e) molding the obtained bioactive glass composition into desired shape and allowing it to cool down to ambient temperature.

03.10.2002

ABSTRACT

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The invention relates to a bioactive glass composition comprising SiO_2 , Na_2O , CaO , K_2O , MgO , P_2O_5 and B_2O_3 . According to the invention, the amount of SiO_2 is 51-56 wt-% of the starting oxides, Na_2O is 7-9 wt-% of the starting oxides, CaO is 21-23 wt-% of the starting oxides, K_2O is 10-12 wt-% of the starting oxides, MgO is 1-4 wt-% of the starting oxides, P_2O_5 is 0,5-1,5 wt-% of the starting oxides, B_2O_3 is 0-1 wt-% of the starting oxides, provided that the total amount of Na_2O and K_2O is 17-20 wt-% of the starting oxides. The invention further relates to the use of said bioactive glass composition and the manufacturing of said bioactive glass composition.

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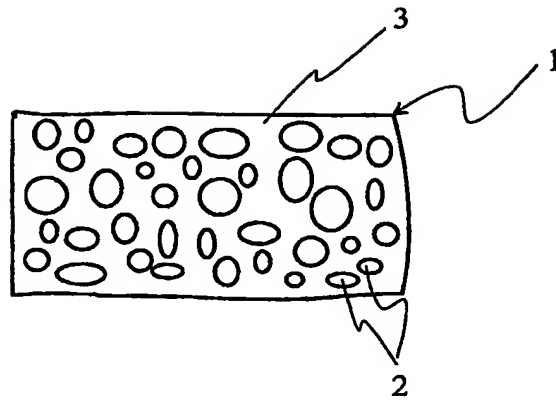


Fig. 1

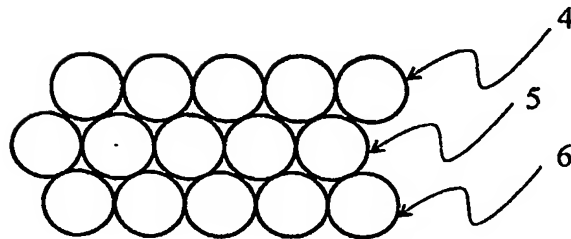


Fig. 2

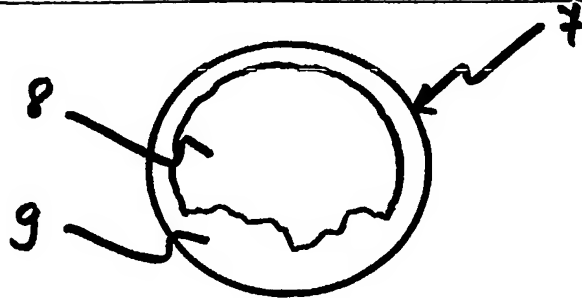


Fig. 3a

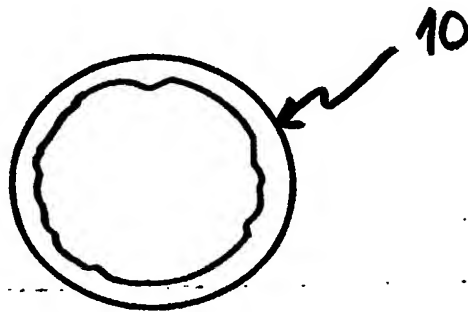


Fig. 3b

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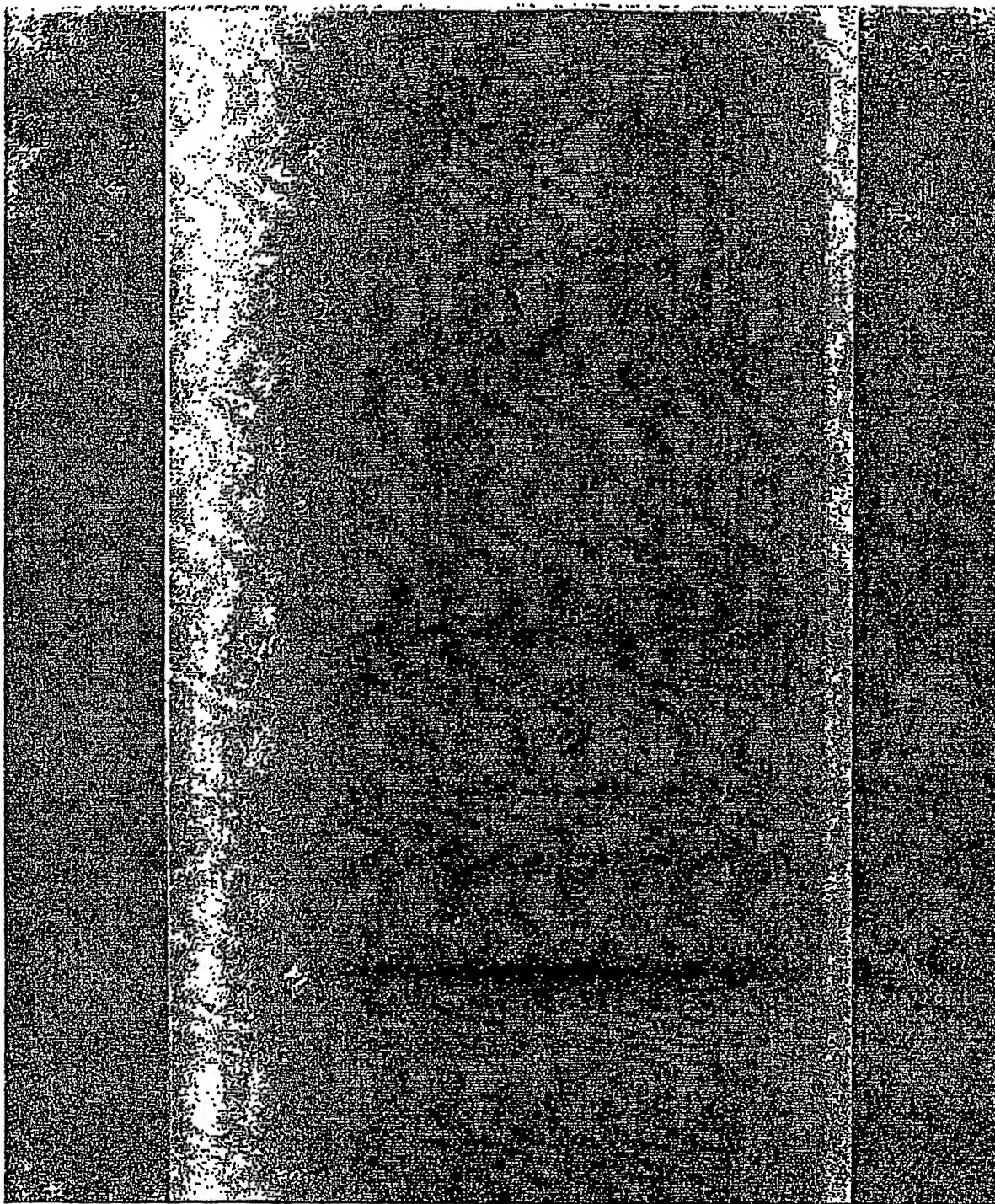


Fig. 4a

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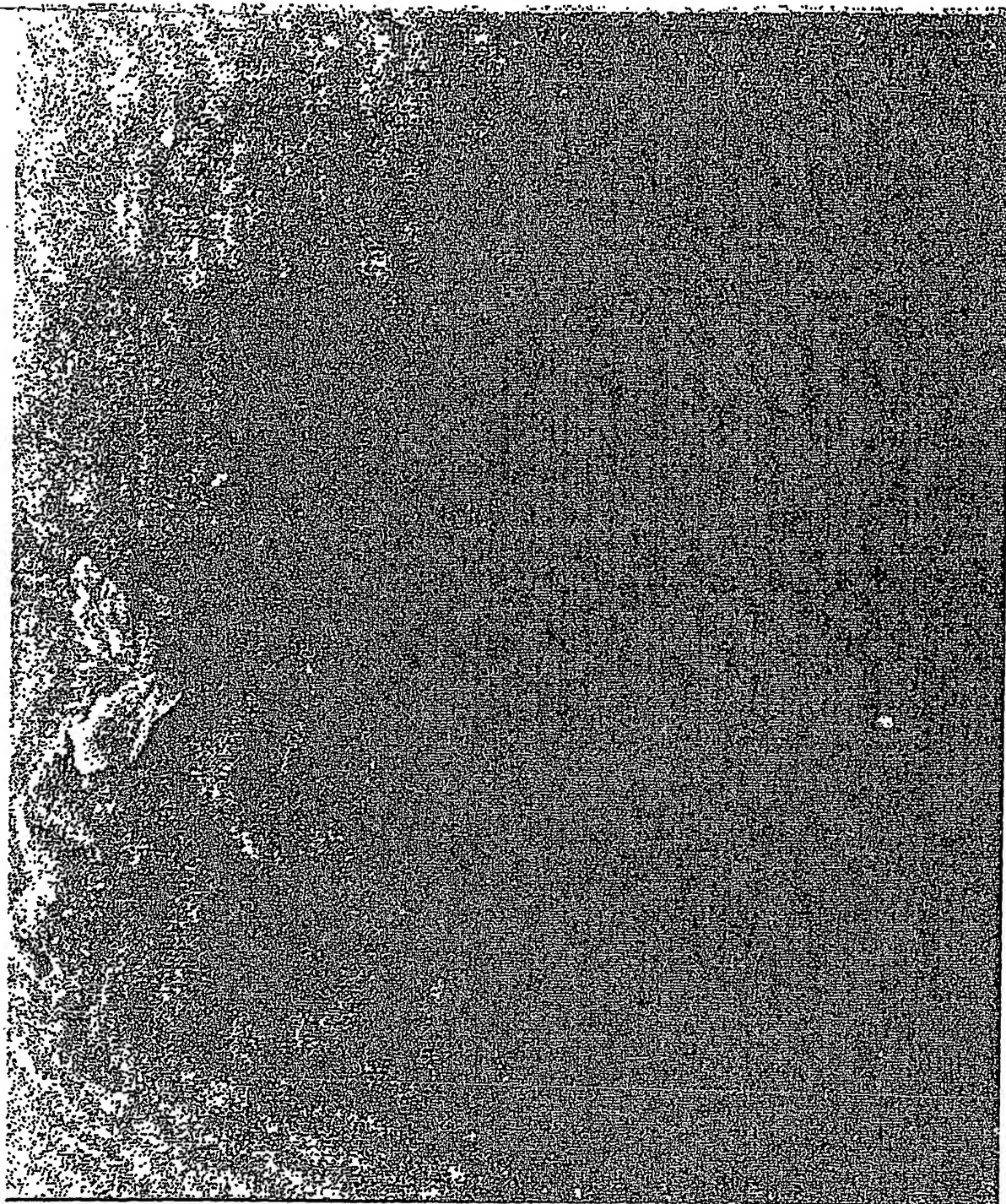


Fig. 4b

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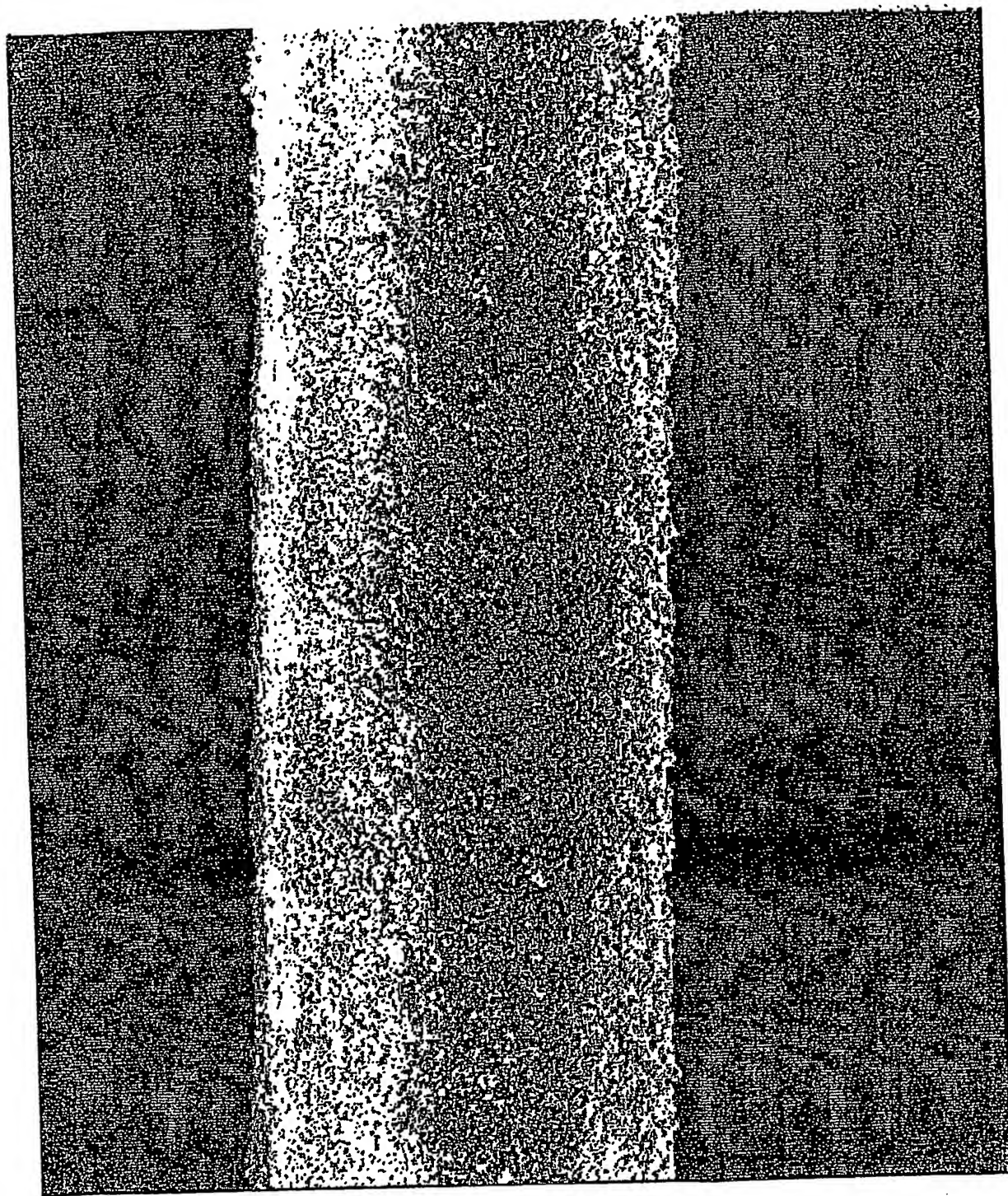


Fig. 5a

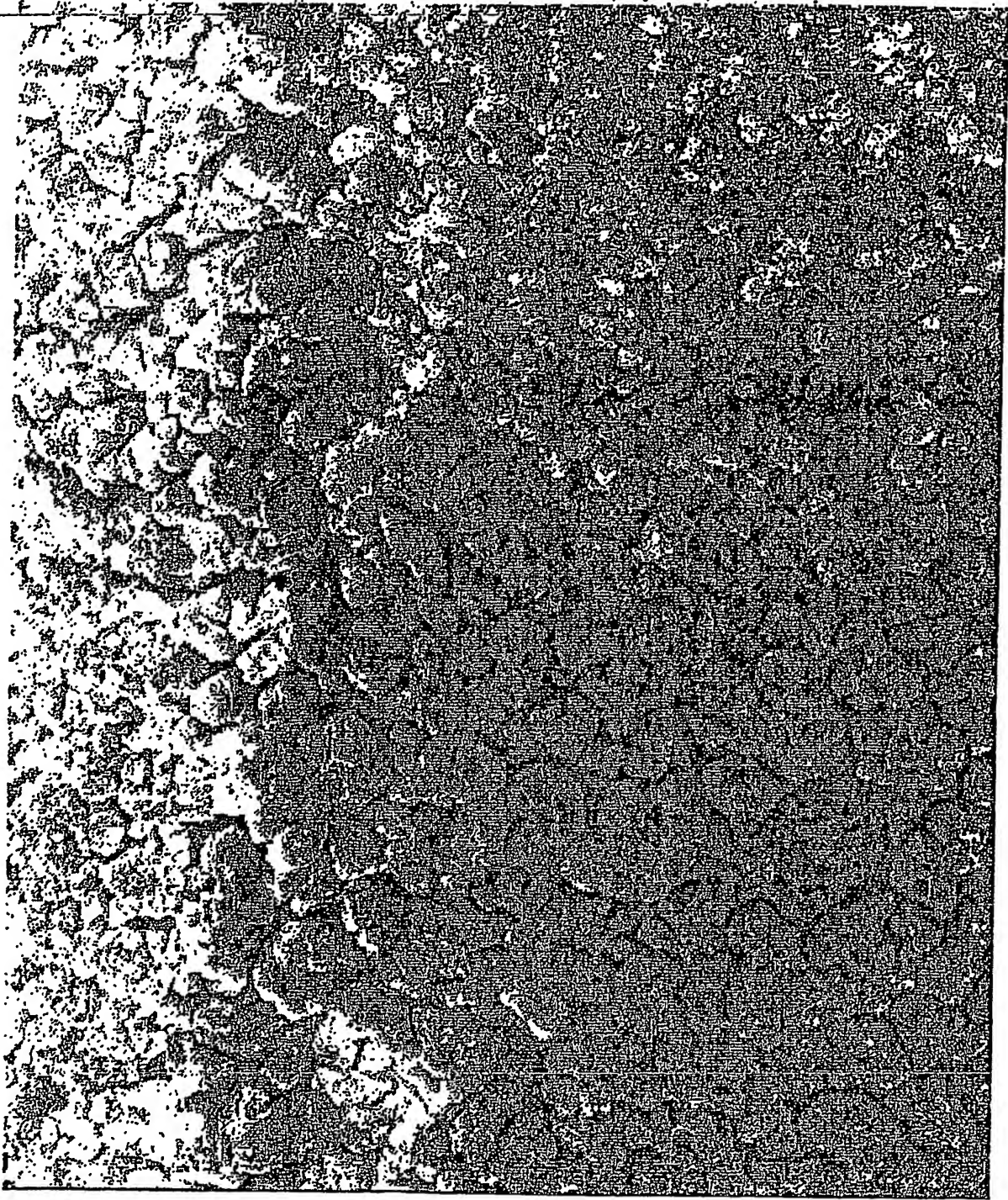


Fig. 5b

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